Review Article

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Embedment of Carbon Nanotubes in Carbon Fibre Reinforced Polymer for Carrier Plates in Space Payload

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ABSTRACT

Microwave for space payload is designed for the wide range of microwave frequencies. They are also capable of withstanding the stringent space and launching environment. It provides electrical interfaces between the components in the spacecraft system and has to ensure high reliability. The package consists numbers of carrier plates on which substrates are attached. A carrier plate is used as a metallic carrier to support to alumina substrate on which the microwave circuit is etched. The indigenous development of CFRP based carrier plates is a possible replacement of standard Kovar based carrier plates to reduce the mass by six times lighter than the existing topology. However, CFRP is having significantly lower conductivity compare to Kovar material. The lower conductivity directly affects the heat dissipation electromagnetic shielding, current carrying capability and surface treatment process. To overcome these problems & achieve full advantage, advanced Nano-filler material, Carbon Nanotubes (CNTs) can be added to the polymer. The use of CNT composites will not only reduce the weight but improve thermal and electrical parameters. This paper provides a research overview of the enhancement of thermal and electrical properties of CFRP, helps to design microwave package assembly. The challenge is to identify the suitable fabrication technique, process parameters, and characterization of the CNT composite.

Keywords: Carbon Fiber Reinforced Polymers; Carbon Nanotubes Composites; Carrier Plates; Microwave Package; Space payload.

1. INTRODUCTION

A microwave package is designed to operate specifically over microwave frequencies of the order of a few GigaHertz (GHz), which requires line-of-sight propagation between satellite and ground hardware. These packages are designed to provide enclosure for integrated microwave circuits (MIC) and printed circuit boards(PCB), as shown in Fig 1. The package consists of substrate mounted carrier plates, stepped cover, electronic devices, which are also mounted on substrates as well on tray surface (Michael Pecht, 1991). The purpose of this is to integrate all the components of a sub-system in such a way as to minimize size, mass, complexity and cost. Compartment height, width and length are based on the size of components & their location, types of R.F. connectors, feed through, substrates and electronics devices. The numbers of mounting hardware are determined after overall size, weight and load are finalized. Moreover, the microwave packages have to withstand stringent launch and space environments are another factor in designing. These requirements call for high-density assemblies, miniaturization of components and optimization of thermo-mechanical stresses on components.

The integrated microwave circuits (MIC) are engraved on alumina substrate (Agrawal and brij 1986). In a typical carrier plate assembly, an alumina substrate is bonded to a Kovar plate using a solder preform (Fig. 2). The carrier plates are used in different sizes & shapes so that MIC substrate are properly soldered on them. They are firmly secured with the enclosure on their extension, which is known as mounting lugs. Carrier plates are made of Kovar material with high cobalt & nickel content to have a low coefficient of linear thermal extension. Different sizes and various topology of carrier plates are used for the microwave package, as shown in Fig 2. The thickness of this carrier plate is 0.8 mm at the functional area (alumina substrate mounting area), and mounting lugs have a thickness of 1.5 mm. Kovar material is poor in corrosion resistance and therefore gold plated in the range of 4 to 6 micron. Gold provides an excellent corrosion resistance due to noble in nature, good electrical conductivity and good solderability for attaching gold plated alumina substrate (Dhaval A. Vartak and Manglik, 2014).

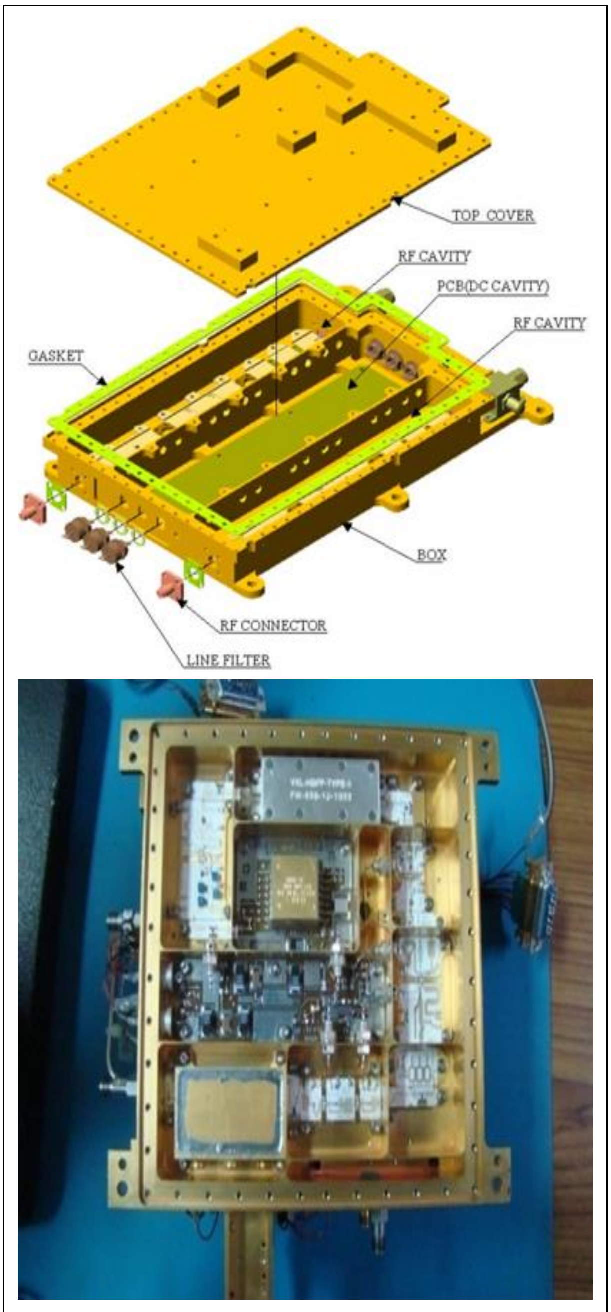
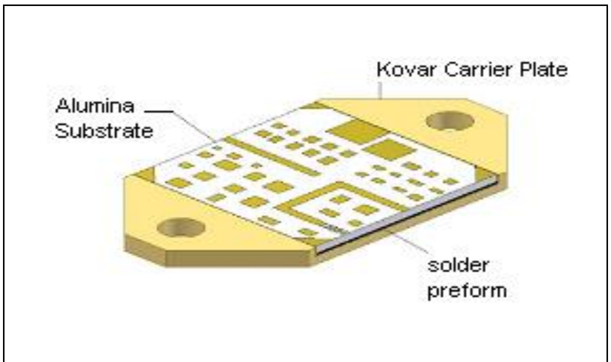


Fig. 1: Microwave Electronics Package for Communication Payload



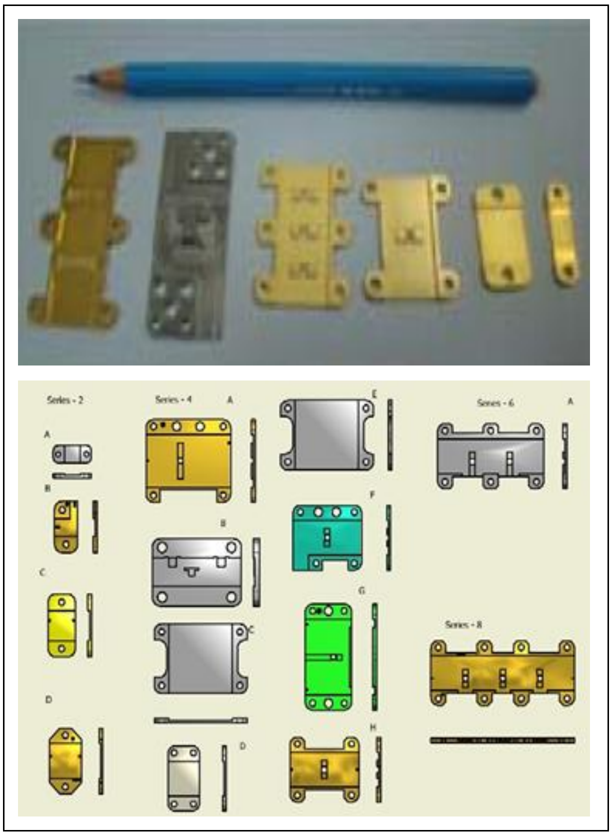


Fig. 2: Different Types of Carrier Plates of Microwave Electronics Package (Dhaval A. Vartak, 2014)

CARBON FIBRE REINFORCED POLYMER (CFRP)

Miniaturization and mass reduction are important factors for the space payload systems. For space payload, mass is important as the heavier a spacecraft launching is more expensive. The launch cost of the satellite reaches up to Rs. 4000/gram. Even a gram reduction in weight can save thousands of rupees in launching cost; therefore, the use of lightweight materials has always been desirable. Carbon fibres are the strongest fibers, which are used to make composites with plastics, producing Carbon Fiber Reinforced Polymer (CFRP). CFRP has greater prospective and capabilities due to its favourable property of specific stiffness. Therefore, it is proposed suitable material for microwave package for space applications.

CFRP based carrier plate is developed for the RF circuits attachment CFRP based carrier plates realization such as Gold electroplating (strike) of the carrier plates, Process for substrates attachment, Ribbon/wire bond and connector soldering, Electrical & Environmental tests are already carried out (Kamaljeet Singh *et al.* 2018). The development of CFRP carrier plate encompasses all indigenous processes for the same and can be easily reproducible. The added advantage is the faster turnaround time, ease of re-work, corrosion resistance.

However, one of the disadvantages of CFRP, has a significantly lower conductivity compared to Kovar. The lower conductivity directly affects the heat transfer, electromagnetic shielding, and current-carrying capability and surface treatment process. Moreover transversal (in-depth) conductivity of CFRP is very low because of the laminar epoxy layers. Resin conductivity increases the conductivity of CFRP (Matra Martins *et al.* 2018). A possible solution is to increase the conductivity of the resin is the use of Carbon Nanotubes (CNTs) material. CNTs have significant attractive mechanical, electrical & thermal properties, superior to state-of-art materials currently being used. In recent years, these CNTs is to be considered the most popular materials as fillers for CFRP materials because they can improve electrical conductivity, mechanical and thermal properties of polymer without increasing the weight (Joana F. Guedes *et al.* 2019; Dhaval A. vartak *et al.* 2020).

ENHANCEMENT OF THERMAL & ELECTRICAL PROPERTIES

The thermal properties of the polymer matrix also modified by CNT addition, like CNT increases the thermal conductivity, glass transition, melting, and thermal decomposition temperatures (Fig.3). The multi-walled carbon nanotubes (MWCNTs) are found to most significantly improve the thermal conductivity of polymer composites among all CNT types.

Electrical percolation of transitions in the carbon nanotube/epoxy composites occurs at concentrations below 0.1 wt%, as shown in Fig 4. There is a decrement in volume and surface resistivity at 0.5% wt of CNT (Erik T. Thostenson and Tsu-Wei Chou, 2002; Bal and Samal, 2007). The well-dispersed CNTs can improve significantly electrical conductivity (Songlin Zang *et al.* 2019). The glass transition temperature (T_g) depends on the motion of polymer chains, and a free volume in the presence of the CNTs, Addition of CNTs decreases the free volume, results in increasing the T_g (Table 1).

Table 1. Increase in Tg and Reduction the Volume Resistivity & Surface Resistance (Sagar Roy *et al.* 2018)

Sample	Tg (°C)	Micro hardness (HV)	Volume Resistivity (ohm-cm)	Surface resistance 1cm² area (ohm)
Epoxy Pure	77.3	17.2	1.31×10^{11}	7.1×10^{9}
Epoxy-CNT-Raw	95.3	20.8	0.8×10^{9}	0.9×10^{9}

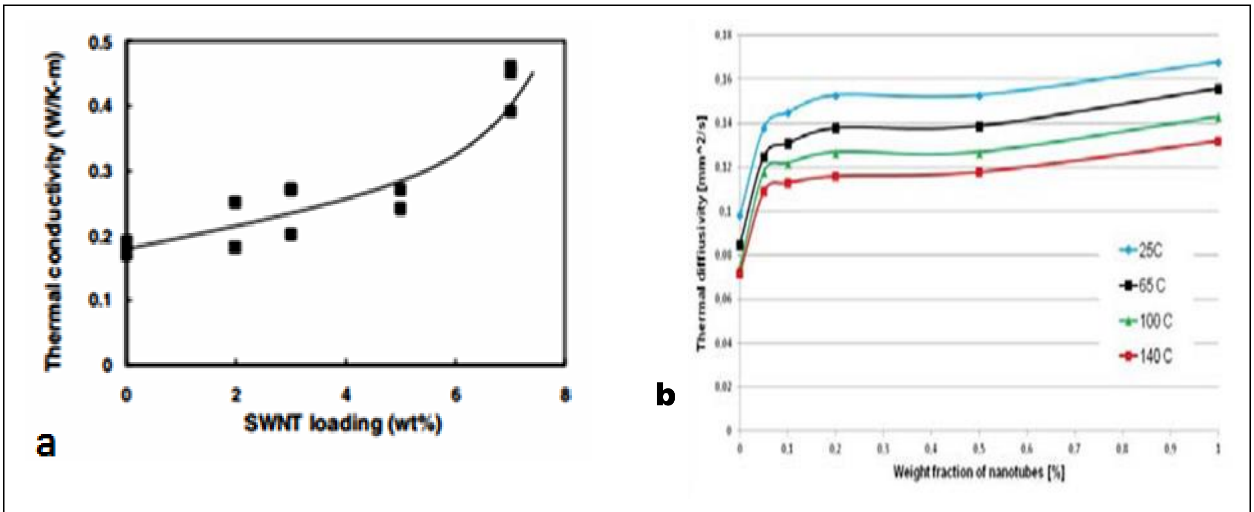


Fig. 3: (a)Thermal Conductivity Vs. Single-Walled Carbon Nanotube (Du *et al.* 2006) and (b) Thermal Diffusivity Vs Carbon Nanotube with different temperature (Ewelina Ciecierska)

Moreover, Microwave Packages are made up of Aluminum boxes that can be replaced by pitch based CFRP-CNT composites. Feasibility studies to obtain thermally conductive CFRP materials using an out-of-autoclave RTM process with demanding characteristics typically obtained in autoclave processes. A mass reduction of 23% may be obtained when compared to an equivalent aluminum housing. MWCNT-CFRP exhibits higher Electro Magnetic Interference (EMI) Shielding Effectiveness(SE) thanAA6061-T6 due to higher absorption and multilayered structure. EMI SE of -80 dB can be achieved in a wide frequency band with the incorporation of 0.2wt% MWCNTs in CFRP (Fawad Tarique *et al.* 2017) (Fig 5a). EMI shielding is a significantly important property for MIC packages. Electrical conductivity significantly increases with CNT loading to as shown in Fig 5b.

Thermal stresses are induced due to the periodic temperature fluctuations in MIC packages. The large difference in CTE of fiber and matrix may cause thermal fatigue in neat CFRP package. Thermal experiments demonstrate that the MWCNT-CFRP is thermally stable up to 354ºC and has considerably lower CTE than AA6061-T6 as shown in Table 3. It is found that MWCNT-CFRP can survive the thermal cycling in a range of -40ºC to 120ºC without any detectable cracking and de-lamination.

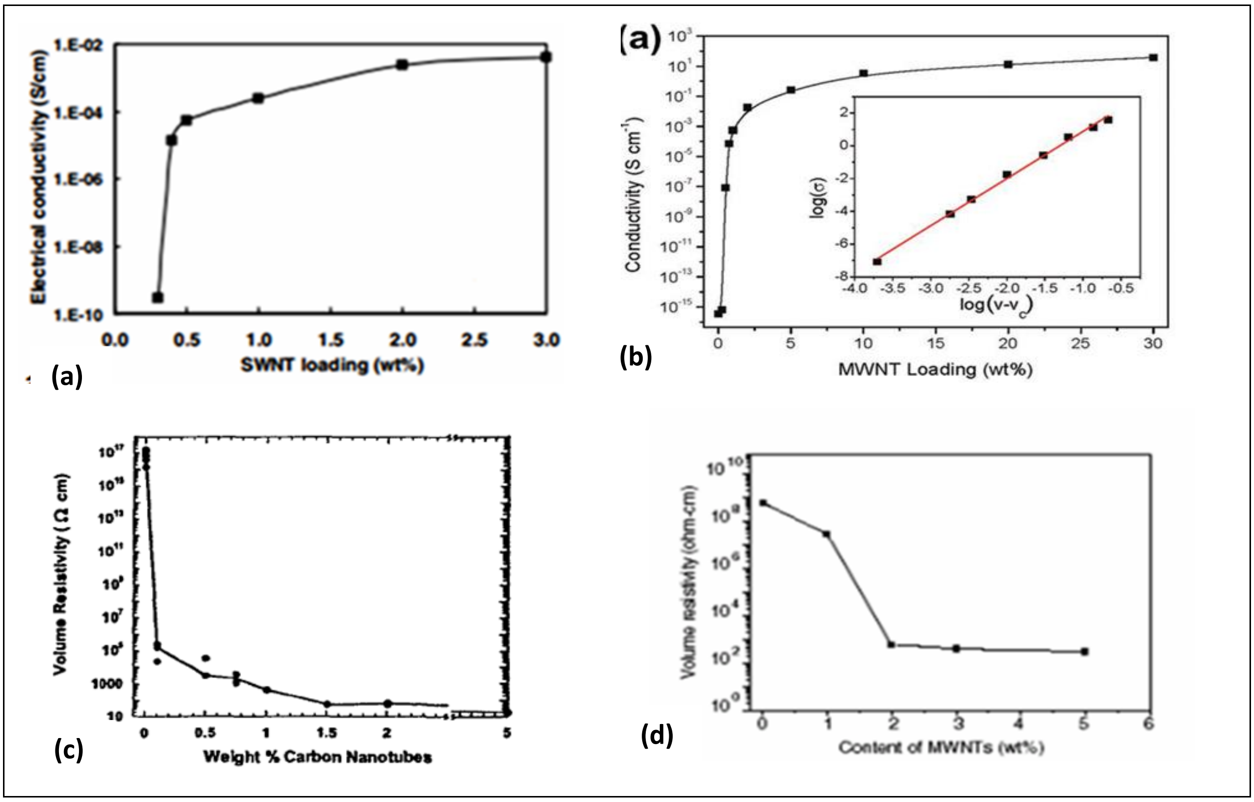


Fig. 4: (a & b) Electrical conductivity increases with SWNT/MWCNT (Irina Gouzman *et al.* 2019; Bellucci *et al.* 2007) (c & d) Volume Resistivity Vs SWNT/MWCNT (Erik T. Thostenson and Tsu-Wei, 2005; Rupesh Khare and Suryasarathi Bose, 2005)

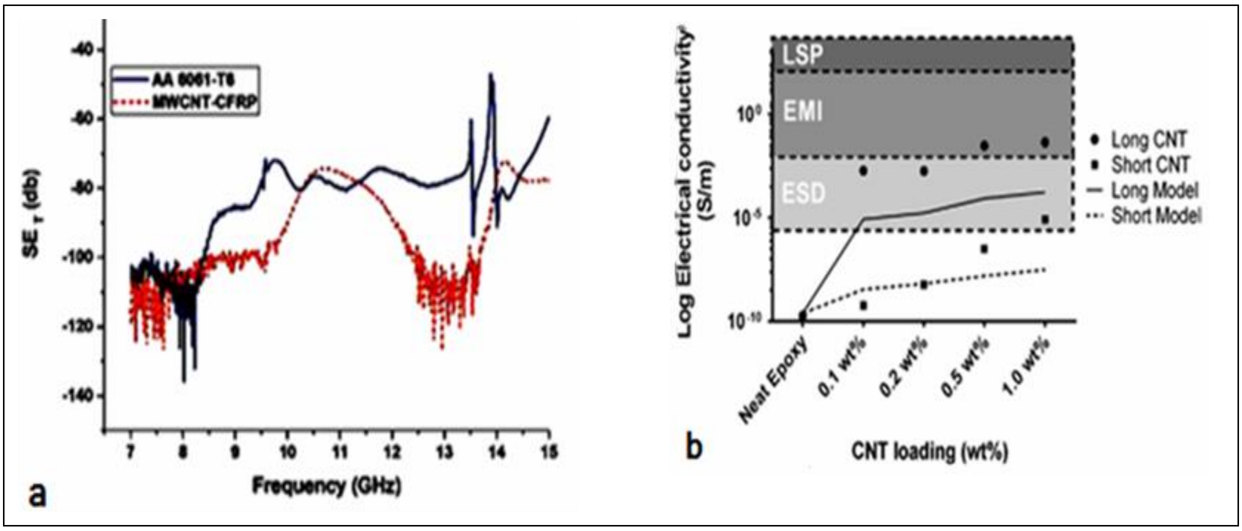


Fig. 5: a) Comparison of EMI shielding effectiveness of MWCNT-CFRP and AA6061-T6 (Fawad Tariq et al. 2017) b) Effect of Electrical conductivity EMI, ESD applications vs %wt CNT(Michael Russ et al. 2013)

Table 2. Comparison of Al alloy, CFRP and MWCNT-CFRP (Fawad Tariq *et al.* 2015)

Parameters	Al6061-T6	Neat CFRP	MWCNT-CFRP
T_g (^0C)	-	125	120
CTE in 35-55^0/C	23.6 x 10^{-6}	-7.55 x 10^{-6}	-3.9 x 10^{-6}
CTE in 55-100^0/C	23.6 x 10^{-6}	3.4 x 10^{-6}	3.1 x 10^{-6}
T_D (^0C)	-	356	354

CHALLENGES

The addition of CNTs significantly increases the viscosity of the matrix (Kenan Song *et al.* 2013). The polymer solution allows dispersing nanotubes relatively easy, but some challenges are faced, depending on the polymer matrix used, carbon nanotube type and processing conditions. It is identified that there are two major interrelated issues of processing parameters of CNT composites (i) lack of uniform dispersion when mixed with polymer resins and (ii) poor interfacial adhesion between CNTs and various polymers. Although uncertainties of these two issues are often problematic at different stages of nanocomposite fabrication. Space qualification is an important process to demonstrate whether CNT composites are capable of sustaining under space environment, with the highest reliability. The CNT composites have to undergo various severe environmental tests like Thermal Cycling, Humidity, Thermovac, Radiation Resistance, EMI/EMC & Outgassing Properties (CVCM-TML) and measurements like mechanical strength, electrical, thermal conductivity, CTE. And only qualified materials are to be used for the fabrication of the flight-worthy components for space payload.

CONCLUSION

The developments of CFRP based carrier plate and MIC packages reduces the mass by more than 60% than traditional space-qualified materials. Solution mixing is the most common & easy method for the fabrication of CNT/polymer nanocomposites because it is suitable for small sample sizes. The dispersion process with a suitable solvent like Aceton and Propanol can be carried out by mechanical mixing, magnetic stirring or sonication. The solvent can reduce the viscosity and dissolve or evaporate from Epoxy at elevated temperatures. Subsequently, the dispersed CNTs Epoxy solution is mixed with Hardener, and the nanocomposite is finally obtained by precipitating or casting the mixture.

Table 3. Comparison of Kovar material with CFRP and CNT-CFRP (Sayed Ahmed *et al.* 1997; Mitel Petch *et al.* 2014)

Material	Kovar	CFRP	CNT-CFRP
Density g/cc	8.3	1.5-1.7	1-2
Thermal conductivity W/mK	17	In-Plane 1.8 Thru thickness 0.609	Increase by 30% in-plane, 10% thru thickness
Electrical Resistivity Ωm	50 x 10^{-8}	Longitudinal 3.4 E^{-5} Thru thickness 12.5E^{-5}	Decrease by by 12 times in-plane and 60% in thru thickness
Coefficient of Thermal Expansion/$10^{-6}K^{-1}$ (25-200^{0}C)	5.5	Less than 1	Less than 1

The increase in the electrical conductivity of this polymer material by the addition of CNT is the major advantage of fabricating CNT/polymer nanocomposite. A significant improvement in thermal & electrical conductivity is observed at very low CNT loading for MWCNT (0.5%-1%wt) whereas SWCNT (0.3-0.5%wt). CNT composites carrier plates provide very high stiffness, strength, low density, reduced thermal stress, Warpage, distortion, and achieve tailorable thermal and electrical properties associated with this development. Enhancement of thermal and electrical properties improves thermal dispersion and electromagnetic shielding, current carrying capability, leads to surface plating process, respectively. Table 3 shows the comparison for replacement of Kovar carrier plate to CNT-CFRP composite. It is advantageous to fabricate CNT CFRP composite Carrier plates in terms of mass reduction compare to Kovar and enhancement of thermal and electrical conductivity compared to CFRP.

This development has the potential to replace all the Kovar based carrier plates presently employed in all frequency transponders and payloads applications resulting in considerable weight reduction and improvement of thermal &electrical properties required for functional aspects.

The Space Qualification process for CNT-CFRP composites and characterisation for mechanical, thermal and electrical properties have to be carried out to

determine the required properties of the composites for the carrier plate of the microwave package.

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